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Title: System and Method for Measuring Optical Distance

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GOVERNMENT SUPPORT

BACKGROUND OF THE INVENTION

Phase-based optical interferometric techniques are widely employed in optical distance measurements in which sub-wavelength distance sensitivity is required.

5   Optical distance is defined as the product of the refractive index and the length. However, most such techniques are limited by an issue which is widely known in the field as 2π ambiguity or integer ambiguity which can be defined as the difficulty in telling the interference fringes of an axial scan apart from each other. An unmodified harmonic phase based low coherence interferometry method (HPI) can be used to

10   determine the differential optical distance, $\left(n_{\lambda_2} - n_{\lambda_1}\right)L$, where L is the physical distance, n_{λ_1} and n_{λ_2} are the refractive indices at the wavelengths λ_1 and λ_2 respectively, if the optical distance is increased gradually so that the differential phase measured by HPI can be tracked through its 2π wrap over. To determine $\left(n_{\lambda_2} - n_{\lambda_1}\right)$ for DNA in solution, for example, the DNA concentration is gradually increased in the

15   measuring cuvette. While such a measurement approach works well in a controlled environment, it can hardly be implemented in a situation where there is less

manipulability in the sample. For example, the method does not work on a fixed slab of material which we are constrained to keep whole.

The problem lies in the fact that unmodified HPI is unable to tell the interference fringes of an axial scan apart from each other, described herein as the 2π ambiguity

5   issue. It is a problem that plagues most phase-based optical interferometric techniques. As a result, these techniques are unable to determine optical distance absolutely. Therefore, most such techniques are used in applications, such as evaluating the texture of continuous surfaces or detecting time-dependent distance changes, in which phase unwrapping is possible through comparison of phases between adjacent points or over

10   small time increments.

SUMMARY OF THE INVENTION

The methods of the present invention are directed at an accurate phase-based technique for measuring arbitrarily long optical distances, preferably with sub-

15   nanometer precision. A preferred embodiment of the present invention employs an interferometer, for example, a Michelson interferometer, with harmonically related light sources, one continuous wave (CW) and a second source having low coherence (LC). The low coherence source provides a broad spectral bandwidth, preferably a bandwidth of greater than 5 nm for a 1 micron (μ) wavelength, for example, the required bandwidth

20   can vary as a function of wavelength and application. By slightly adjusting the center wavelength of the low coherence source between scans of the target sample, the phase relationship between the heterodyne signals of the CW and low coherence light can be

used to measure the separation between reflecting interfaces with sub-nanometer

precision. As this technique is completely free of 2π ambiguity, an issue that plagues

most phase-based techniques, it can be used to measure arbitrarily long optical distances

without loss of precision. An application of a preferred embodiment of the method of

5   the present invention is the precision determination of the refractive index of a sample at

a given wavelength of a sample with a known physical thickness. Another application

of a preferred embodiment of the method of the present invention is the precision

determination of a sample's physical thickness with a known refractive index. A further

application of a preferred embodiment of the method of the present invention is the

10   precision determination of the refractive index ratio at two given wavelengths.

In an alternate preferred embodiment, the low coherence light source provides a

sufficiently broad bandwidth light, preferably greater than 5 nm, to provide

simultaneously a first low coherence wavelength and a second low coherence

wavelength with the respective center wavelengths separated from each other by more

15   than approximately 2 nm. The frequency spectrums for the low coherence wavelengths

do not significantly overlap. An additional detector and filters are disposed in the

interferometer to transmit and detect the two low coherence wavelengths.

The preferred embodiment methods can be used to make precise optical distance

measurements. From such measurements, optical properties of target objects can be

20   accurately measured. By measuring the dispersion profile of the target, structural and/or

chemical properties of the target can be evaluated. The dispersion profile maps out the

refractive index differences at various wavelengths. In the biomedical context,

preferred embodiments of the present invention can be used to accurately determine the

dispersion properties of biological tissues in a non-contact and non-invasive manner.

Such dispersion determination can be used on the cornea or aqueous humor of the eye.

The sensitivity achieved can be sufficient to detect glucose concentration dependent

5   optical changes. In a preferred embodiment of the present invention method, the blood

glucose level can be determined through non-invasive measurements of the dispersion

profile of either the aqueous, vitreous and/or aqueous and/or aqueous humor or the

cornea of the eye. A preferred embodiment of the present invention can be applied as a

measurement technique in semiconductor fabrication to measure small features formed

10   during the manufacturing of integrated circuits and/or optoelectronic components. As

the preferred embodiment of the method is non-contact and non-destructive, it can be

used to monitor the thickness of semiconductor structures or optical components as they

are being fabricated.

15   BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of a preferred embodiment of the system to

measure an optical distance in accordance with the present invention;

Figure 2 illustrates the low coherence heterodyne signals associated with a

reflecting interface in accordance with a preferred embodiment wherein adjusting the

20   low coherence wavelength compresses or expands (depending on the direction of

adjustment of the center wavelength of the low coherence source) the heterodyne signal

around the interface;

Figure 3 illustrates heterodyne signals associated with two reflecting interfaces in a sample in accordance with a preferred embodiment wherein decreasing the low coherence wavelength compresses the heterodyne signal around the interfaces;

Figure 4 illustrates a scan of a sample with two interfaces in accordance with a

5   preferred embodiment of the present invention (a) low coherence heterodyne signal, (b) trace wherein the magnified view shows the phase fringes, each fringe corresponds to an optical distance of λ_{CW}, (c) traces at two difference values of Δ, wherein the arrows indicate the phase crossing points, the vertical axis is in radians;

Figure 5 illustrates a method of determining correct estimates of ($n_{755nm}L$)

10   measured by choosing the values that minimizes the error between estimates based on S_{phase} and S_{fringe} in accordance with a preferred embodiment of the present invention;

Figures 6A and 6B are a flow chart illustrating a method to measure an optical distance in accordance with a preferred embodiment of the present invention;

Figure 7 is a schematic diagram of an alternate preferred embodiment of the

15   system to measure an optical distance in accordance with the present invention;

Figures 8A and 8B are a flow chart illustrating an alternate method to measure an optical distance in accordance with a preferred embodiment of the present invention;

Figure 9 schematically illustrates a preferred embodiment of a fiber based system to measure the thickness of an optically transmissive material such as a glass

20   slab, tissue sample or layer; and

Figure 10 illustrates a preferred embodiment of the present invention system used in a vitreous and/or aqueous humor glucose measurement system in accordance with the present invention.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

5   DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed at phase crossing based systems and methods for measuring optical distances that overcome the integer or 2π ambiguity problem by introducing a dispersion imbalance in an interferometer. A preferred embodiment of the method is able to measure the relative height difference of two adjacent points on a

10   surface with precision. Further, the refractive index of a sample can be found to an accuracy that is limited only by the precision with which the physical thickness of the sample can be experimentally measured.

The substitution of one of the low coherence light sources with a continuous wave (CW) light source in the harmonic phase based interferometry (HPI), allows the

15   use of the associated CW heterodyne signal as a form of optical ruler by which the low coherence heterodyne signal can be measured. The low coherence light source provides

a spectral bandwidth, for example, greater than 5 nm for 1 micron wavelength. One of the benefits of using such a modified HPI is that the measured phase is now sensitive to the length scale nL instead of $\left(n_{\lambda_2} - n_{\lambda_1}\right)L$, where n is the refractive index at the low coherence wavelength. The quantity n is more practically useful than the composite

5    $\left(n_{\lambda_2} - n_{\lambda_1}\right)$. By adjusting the low coherence wavelength slightly, for example, by approximately 2 nm, the quantity nL can be found without 2π ambiguity and with sub-nanometer sensitivity. This method uses the CW heterodyne interference signal as a reference optical ruler by which the optical distance is measured.

Interferometric optical distance measuring systems employing readily available

10   low coherence light sources have achieved resolution on the order of tens of wavelengths. While this technique is relatively insensitive, it does not have to contend with the 2π ambiguity issue. A preferred embodiment includes a low coherence interferometry method that uses phase to measure arbitrarily long optical distances with sub-nanometer precision. This method uses a low coherence phase crossing technique

15   to determine the integer number of interference fringes, and additional phase information from the measurement to accurately obtain the fractional fringe. In addition, it provides depth resolution and can be used for tomographic profiling of stratified samples. As the method can measure long optical distances with precision, it can be used to determine refractive indices of a plurality of materials accurately. As this

20   is a phase-based method, the refractive index thus found is the phase refractive index and not the group refractive index.

Figure 1 illustrates a preferred embodiment of the system 10 of the present

invention that includes a modified Michelson interferometer. The input light 12 is a

two-color composite beam composed of 150-fs mode-locked light from a Ti:sapphire

laser, for example, emitting at 775.0 nm and continuous wave (CW) 1550.0 nm light

5   from, for example, a semiconductor laser. In the preferred embodiment the method

evaluates optical distances in terms of the CW wavelength, (1550.0 nm exactly in this

embodiment) and all optical distances are computed based on this basis. The composite

beam is divided in two at the beamsplitter 14. One part signal is incident on the target

sample 16, while the other is incident on a reference mirror 32 moving preferably at, for

10   example, approximately 0.5 mm/s, which induces a Doppler shift on the reference beam

34. The Doppler shift can be induced by other means, such as, for example, through the

use of an electro-optical modulator. The back-reflected beams are recombined at the

beamsplitter 14, separated into their wavelength components by means of a dichroic

mirror 18, and measured separately with photodetectors 20, 22. The resulting signals

15   are digitized by an analog to digital converter (ADC) 24 such as, for example, a 16-bit

100 KHz A/D converter. A data processor such as a personal computer (PC) 26 is in

communication with the ADC 24 to further process the data. The resulting heterodyne

signals at their respective Doppler-shifted frequencies are bandpassed around their

respective center heterodyne frequencies and Hilbert transformed to extract the

20   corresponding phases of the heterodyne signals, Ψ_{CW} and Ψ_{LC}. The subscripts CW and

LC denote the 1550.0 nm continuous wave and 775.0 nm low coherence wavelength

components, respectively.

The center wavelength of low coherence light is then adjusted by approximately

1-2 nm and a second set of Ψ_{CW} and Ψ_{LC} values is measured. From these two sets of

readings, the various interfaces in the target sample can be localized with sub-nanometer

precision. The processing of data for localization is described hereinbelow.

5   Consider a sample which consists of a single interface at an unknown distance x_1

from the beamsplitter 14. The distance from the beamsplitter 14 to the reference mirror

32, x, is a known quantity at each time point in the scan of the reference mirror.

A method to find an approximate value for x_1 is by scanning x and monitoring

the resulting heterodyne signal in the recombined low coherence light beam. When x is

10   approximately equal to x_1, a peak in the heterodyne signal amplitude is expected. The

precision of such a method is limited by the coherence length, l_c, of the light source and

the signal-to-noise quality of the heterodyne signal. Under realistic experimental

conditions, the error in x_1 determined thus, is unlikely to be better than a fifth of the

coherence length.

15   Given that the coherence length of a typical low coherence source is

approximately 10 μm nominally, this means that the error in such a means of length

determination is limited to about 2 μm.

In considering the phase of the heterodyne signal, the varying component of the

heterodyne signal detected can be expressed as:

20

$$\begin{aligned} I_{heterodyne} &= E_{ref}e^{i(2kx-\omega t)}E_{sig}e^{-i(2kx_1-\omega t)} + c.c. \\ &= 2E_{ref}E_{sig}\cos(2k(x-x_1)) \end{aligned} \qquad (1)$$

where E_{ref} and E_{sig} are the electric field amplitude of the reference and signal

electric field amplitude, respectively, k is the optical wavenumber, ω is the optical

frequency. The factor of 2 in the exponents is due to the fact that light travels twice the

path going to the mirror/sample and back to the beamsplitter.

5   Note that when x matches x_1 exactly, the heterodyne signal is expected to peak.

The two returning beams are in constructive interference. This property is therefore

used to localize the interface. x_1 is found by finding the value of x for which the two

beams are in constructive interference. Since phase can be measured accurately, such an

approach gives a length sensitivity of about 5 nm. Unfortunately, this method is

10   calculation intensive because there are multiple values of x for which the heterodyne

signal peaks; specifically, the heterodyne signal peaks at:

$$x = x_1 + a\frac{\lambda}{2},$$ (2)

where a is an integer and λ is the optical wavelength. This is a manifestation

of the 2π ambiguity issue.

15   The preferred embodiment includes a method to distinguish the correct peak.

Note that when $x = x_1$ exactly, the heterodyne signal peaks regardless of the optical

wavelength. On the other hand, the subsequent peaks are wavelength dependent, as

illustrated in Figure 2. Figure 2 illustrates the low coherence heterodyne signals

associated with the reflecting interface 52 in the sample. Therefore, by adjusting the

20   low coherence wavelength, the heterodyne signal is compressed around the interface

and the correct peak associated with the situation where x-x$_1$ exactly can be

distinguished. It should be noted that the heterodyne signal may be compressed or expanded around the interface depending upon the direction of adjustment. An intuitive way of visualizing the localization is to picture the heterodyne signal squeezing in or expanding away from the fringe where $x = x_1$ exactly.

5   The CW light source is needed in such a localization method for two reasons. First, it is very difficult in practice to know the value absolutely and accurately in an interferometer. The CW component of the interferometer permits highly accurate measurements of x to be made as the reference mirror is scanned. In a specific preferred embodiment, to determine the distance between two interfaces in the sample, a count of

10   the number of CW interference fringes that occurred between where x_1 is equal to the distance to the first interface as shown in Figure 1 and where x_2 ($x_2 = x_1 + nL$ wherein n is the refractive index of the sample) is equal to the distance to the second interface is made. Figure 3 illustrates the heterodyne signals associated with two reflecting interfaces in a sample. Adjusting the low coherence wavelength compresses 82, 84 the

15   heterodyne signal 78, 80 around the interfaces.

Second, the prior described method for localization of the interface may partly fail if there is a phase shift associated with the reflection process. For example, if the surface is metallic, the phase shift is non-trivial and the phase of the heterodyne signal takes on some other value when $x = x_1$ exactly. While the prior method allows the

20   correct interference fringe to be identified where $x = x_1$, however sub-wavelength sensitivity may be compromised. The presence of the CW heterodyne signal allows the

difference phase via the HPI method to be found. The knowledge of this value, allows

the localization of the interface with a high level of sensitivity.

The principle of the HPI method can be illustrated through the exemplary

embodiment of a sample of thickness, L, and refractive index, n_{775nm}, at a wavelength

5   of 775 nm. The two interfaces of the sample are at optical distances x_1 and x_2 (where x_2

$= x_1 + n_{775nm}L$) from the beamsplitter, respectively. Note that the method only works if

the optical distance separation is greater than the coherence length, for example,

typically between 1 micron and a 100 microns of the low coherence light source.

Otherwise, the heterodyne phase signals associated with the interfaces merge together

10 and result in inaccurate interface localization. For clarity of explanation, the

incorporation of the phase shifts associated with reflection are deferred until later.

Figure 4 is a scan illustrating the mathematical description. The scan is of a

sample with two interfaces. The signal 100 is a low coherence heterodyne signal. The

trace 102 is $\psi_{CW}(x)$. The magnified view 104 shows the phase fringes. Each fringe

15 corresponds to an optical distance of λ_{CW}. The lower traces of $\psi_D(x)$ are at two

different values of Δ. The arrows 106, 110 indicate the phase crossing points. The

vertical axis is in radians. As the reference mirror is scanned, the phase of the low

coherence heterodyne signal is given by:

$$\psi_{LC}(x)$$

$$= \mathrm{mod}_{2\pi}\left(\arg\left(R_{LC,1}e^{i2k_{LC}(x-x_1)}e^{-(2a(x-x_1))^2} + R_{LC,2}e^{i2k_{LC}(x-x_2)}e^{-(2a(x-x_2))^2}\right)\right)$$

$$\approx h_c(x-x_1)\mathrm{mod}_{2\pi}\left(2k_{LC}(x-x_1)\right) + h_c(x-x_2)\mathrm{mod}_{2\pi}\left(2k_{LC}(x-x_2)\right),$$

$$(3)$$

with $R_{LC,j}$ the reflectivity of the interface j at the low coherence wavelength, k the

optical wavenumber, $a = 4\ln(2)/l_c$, l_c the coherence length, x the distance of the

reference mirror from the beamsplitter, and $h_c(x)$ a piecewise continuous function with

5   value of 1 for $|x| < 2l_c$ and 0 otherwise. The factors of 2 in the exponents are due to the

effective doubling of optical paths in the back reflection geometry. Equation (3) reflects

the fact that phase cannot be measured far beyond the coherence envelopes, due to

noise. Although the coherence envelops modeled are gaussian in profile, the same

phase treatment is valid for profiles of any slowly varying envelope.

10   The phase of the CW heterodyne signal is given by:

$$
\begin{aligned}
\psi_{cw}(x) &= mod_{2\pi}\left(arg\left(R_{cw,1}e^{i2k_{cw}(x-x_1)} + R_{cw,2}e^{i2k_{cw}(x-(x_1+n_{1550nm}L))}\right)\right) \\
&= mod_{2\pi}\left(arg\left(\overline{R}e^{i2k_{cw}(x-\overline{x})}\right)\right) = mod_{2\pi}\left(2k_{cw}(x-\overline{x})\right),
\end{aligned}
\tag{4}
$$

with $R_{CW,j}$ the reflectivity of the interface j at the CW wavelength, n_{1550nm} the

sample's refractive index, $\overline{R}$ and $\overline{x}$ the effective average reflectivity and distance

from the beamsplitter, respectively. If the center wavelengths of the two light sources

15   are chosen such that

$$k_{LC} = 2k_{cw} + \Delta, \tag{5}$$

where Δ is a small intentionally added shift, then a difference phase, ψ_D, of the form

is obtained:

$$
\begin{aligned}
\psi_D(x) &= \psi_{LC}(x) - 2\psi_{cw}(x) \\
&= h_c(x-x_1)mod_{2\pi}\left(4k_{cw}(\overline{x}-x_1) + 2\Delta(x-x_1)\right) + h_c(x-x_2)mod_{2\pi}\left(4k_{cw}(\overline{x}-x_2) + 2\Delta(x-x_2)\right).
\end{aligned}
$$

20    $$(6)$$

-15-

The above quantity provides both the approximate number of fringes in the interval $(x_2 - x_1)$ and the fractional fringe, which provides sub-wavelength precision.

As the parameter Δ is varied by a small amount (corresponding to a wavelength shift of approximately 1-2 nm), the slope of $\psi_D(x)$ pivots around the points where $x = x_1$ and $x = x_2$. In other words, the phase scans at different values of Δ crosses at those points. The optical distance from x_1 to x_2 can be found by counting the fringes that $\psi_{cw}(x)$ goes through between the two phase crossing points. Twice the quantity thus found is denoted by S_{fringe}, which is not an integer value, and corresponds to the number of fringes at the low coherence wavelength. In the event where multiple phase crossing points occur for a single interface, the point that corresponds to the position of the interface can be found by making multiple scans at additional values of Δ. The position of the interface is the only location where $\psi_D(x)$ will cross for all Δ values.

The phase shift information is used to further localize the interface separation. Specifically, the difference between the phase shifts at $x = x_1$ and $x = x_2$ is:

$$S_{phase} = \frac{mod_{2\pi}(\psi_D(x=x_1) - \psi_D(x=x_2))}{2\pi} = \frac{mod_{2\pi}(4k_{cw}(x_2 - x_1))}{2\pi}. \qquad (7)$$

This measures the fractional fringe with great sensitivity.

The absolute optical separation $(x_2 - x_1)$ can be determined with precision from S_{fringe} and S_{phase} through the following equation:

$$(x_2 - x_1)_{measured} = (n_{775nm}L)_{measured} = \frac{\lambda_{cw}}{4}\left(\left[int(S_{fringe}) + U\left(\Delta S - \frac{1}{2}\right) - U\left(-\Delta S - \frac{1}{2}\right)\right] + S_{phase}\right)$$

$$(8)$$

where $\Delta S = res(S_{fringe}) - S_{phase}$ and $U(\ )$ is a unit step function. Here, $int(\ )$ and $res(\ )$

denote the integer and fractional parts of the argument respectively. The first term

localizes the optical distance to the correct integer number of fringes by minimizing the

error between S_{phase} and the fractional part of S_{fringe}. The error of an optical

5   separation determination is limited only by the measurement error of S_{phase}. In an

experiment such error translates to an error in $(n_{775nm}L)_{measured}$ of approximately 0.5

nm. The measurement error of S_{fringe} needs only be smaller than half a fringe so that

the correct interference fringe can be established; having satisfied this criterion, it does

not enter into the error of $(n_{775nm}L)_{measured}$. The maximum measurable optical distance

10   simply depends on the ability of the system to accurately count fringes between two

crossing points and the frequency stability of the light sources.

The above equation is a condensed expression of the method for finding the

correct fringe and the fractional fringe. The operation can be illustrated through the

following example and Figure 5 which shows the determination of the correct estimate

15   of $(n_{775nm}L)_{measured}$ by choosing the value that minimizes the error between estimates

based on S_{phase} and S_{fringe}. Assume that S_{fringe} and S_{phase} are 26.7 and 0.111. From

the measurement of S_{phase}, the optical distance of the value is:

$$(n_{775nm}L)_{measured} = \frac{\lambda_{cw}}{4}(a + 0.111), \qquad (9)$$

where a is an integer. Given the value of S_{fringe}, the possible values of

20    $(n_{775nm}L)_{measured}$ can be limited to the following 3 values: $\frac{\lambda_{cw}}{4}(25.111)$, $\frac{\lambda_{cw}}{4}(26.111)$

and $\frac{\lambda_{cw}}{4}(27.111)$. Given that the value of $\frac{\lambda_{cw}}{4}(27.111)$ is closest to $\frac{\lambda_{cw}}{4}(S_{fringe})$, it is

the correct estimate of $(n_{775nm}L)_{measured}$.

In preferred embodiments for interferometry experiments based on harmonically

related light sources, the appropriately chosen pair of light sources and the method of

5   extracting difference phase allows the minimization and preferably the elimination of

the effect of jitter in the interferometer, which would otherwise make high precision

optical distance measurement impossible. The elimination of jitter also allows the

comparison of scans performed at different times.

To demonstrate the capability of a preferred embodiment of the method, the

10   system is used to probe the optical distance between the top and bottom surface of a

fused quartz cover slip having a physical thickness, L = 237 $\pm$ 3 μm. In this

embodiment there is a π phase shift associated with reflection from the first interface,

that marks a positive refractive index transition. Hence, there is a $e^{-i\pi}$ term associated

with the factors $R_{LC,1}$ and $R_{cw,1}$ in equations (1) and (2). This results in a correction

15   factor of half on S_{fringe} and S_{phase}. Figure 4 shows the result of typical scans at the LC

wavelengths of 773.0 nm and 777.0 nm. The results of four scans are summarized in

Table 1 which represents measurements of $(n_{755nm}L)$ on a piece of quartz cover slip. The

repeatability of the experimental data indicates that the light source are sufficiently

stable in frequency.

20

	$\dfrac{\lambda_{cw}}{4} S_{fringe}(\mu m)$	$\dfrac{\lambda_{cw}}{4} S_{phase}(\mu m)$	$(n_{775nm}L)_{measured}(\mu m)$
Set 1	350.86 ± 0.17	0.3496 ± 0.0004	351.0371 ± 0.0004
Set 2	351.08 ± 0.17	0.3497 ± 0.0004	351.0372 ± 0.0004
Set 3	351.15 ± 0.16	0.3502 ± 0.0004	351.0377 ± 0.0004
Set 4	351.04 ± 0.18	0.3498 ± 0.0004	351.0373 ± 0.0004
Average			351.0373 ± 0.0004

Table 1

The experimental data yields an optical absolute distance measurement with sub-nanometer precision. The optical distance found is associated with the low coherence light source. The CW heterodyne signal serves as an optical ruler. If L of the quartz cover slip is known precisely, n_{775nm} for quartz at the wavelength 775.0 nm can be found to a very high degree of accuracy from $(n_{775nm}L)_{measured}$.

Alternatively, without knowing the exact value of L, the refractive index ratio at two different wavelengths can be determined by measuring the corresponding optical distances using low coherence light at these wavelengths and CW light at their respective harmonics. Using a range of low coherence wavelengths, the dispersion profile of a material can be determined accurately. The dispersion profile maps out the refractive index differences at various wavelengths. The experimental results in accordance with a preferred embodiment predict that a precision of approximately seven significant figures can be achieved with an approximately 1 mm thick sample.

In another preferred embodiment the light sources of the system are changed to a low coherence superluminescent diode (SLD) emitting at 1550.0 nm and a CW Ti:Sapphire laser emitting at 775.0 nm. By adjusting the operating current through the SLD the center wavelength is changed by about 2 nm; this is adequate to achieve phase

crossing. Using this preferred embodiment of the present invention system, the optical

distance can be measured at 1550.0 nm. Taking the ratio of the result of this

measurement with the previous measurement, the ratio of the refractive indices

n_{775nm} / n_{1550nm} for quartz can be determined. It should be noted that the index ratios

5   found are for harmonically related wavelengths due to the sources used in the preferred

embodiments. Refraction index ratios for other wavelengths can be measured with

other appropriate choices of light sources. For comparison, the corresponding data for

glass and acrylic plastic are tabulated in Table 2 as measurements of n_{775nm}/n_{1550nm} for

different materials.

	n_{775nm} / n_{1550nm}
Quartz	1.002742 ± 0.000003
Glass (German borosilicate)	1.008755 ± 0.000005
Acrylic plastic	1.061448 ± 0.000005

Table 2

10

Note that some of the equations used when the low coherence wavelength is half

that of the CW wavelength are slightly different from the equations previously presented

herein. For example:

$$\psi_{LC}(x)$$

$$= mod_{2\pi}\left(arg\left(R_{LC,1}e^{i2k_{LC}(x-x_1)}e^{-\left(\frac{2}{l_c}(x-x_1)\right)^2} + R_{LC,2}e^{i2k_{LC}(x-x_2)}e^{-\left(\frac{2}{l_c}(x-x_2)\right)^2} \right) \right)$$

$$\approx h_c(x-x_1)mod_{2\pi}\left(2k_{LC}(x-x_1)\right) + h_c(x-x_2)mod_{2\pi}\left(2k_{LC}(x-x_2)\right),$$

15   (10)

$$\psi_{cw}(x) = mod_{2\pi}\left(arg\left(R_{cw,1}e^{i2k_{cw}(x-x_1)} + R_{cw,2}e^{i2k_{cw}(x-(x_1+n_{1550nm}L))}\right)\right)$$

$$= mod_{2\pi}\left(arg\left(\overline{R}e^{i2k_{cw}(x-\overline{x})}\right)\right) = mod_{2\pi}\left(2k_{cw}(x-\overline{x})\right),$$

$$(11)$$

$$2k_{LC} = k_{cw} + \Delta,$$

$$(12)$$

5

$$\psi_D(x) = 2\psi_{LC}(x) - \psi_{cw}(x)$$

$$= h_c(x-x_1)mod_{2\pi}\left(4k_{LC}(\overline{x}-x_1) + 2\Delta(x-x_1)\right) + h_c(x-x_2)mod_{2\pi}\left(4k_{LC}(\overline{x}-x_2) + 2\Delta(x-x_2)\right)$$

$$(13)$$

$$S_{phase} = \frac{mod_{2\pi}(\psi_D(x=x_1) - \psi_D(x=x_2))}{2\pi} = \frac{mod_{2\pi}(4k_{LC}(x_2-x_1))}{2\pi}.$$

$$(14)$$

10
$$(x_2-x_1)_{measured} = (n_{775nm}L)_{measured} = \frac{\lambda_{LC}}{4}\left(\left[int(S_{fringe}) + U\left(\Delta S - \frac{1}{2}\right) - U\left(-\Delta S - \frac{1}{2}\right)\right] + S_{phase}\right)$$

$$(15)$$

Preferred embodiments of the methods for overcoming 2π ambiguity is of

significant use in applications such as high precision depth ranging and high precision

refractive index determination of thin film solid state materials.

15   The use of the preferred methods can be illustrated through consideration of a

slab of glass. There exist systems that can measure the distance from the systems to the

averaged center of the glass slab very accurately. There are also systems that can

measure the roughness of the glass surface very accurately. A preferred embodiment of

the present invention system measures with nanometer sensitivity the thickness of the

20   glass slab end-face.

The steps in the implementation of a preferred embodiment of the method to

determine the optical distance are illustrated in the flow chart 124 in Figures 6A and 6B.

The method 124 includes the use of two harmonically related light sources in a Michelson interferometer, one of which is a CW source while the other is a low coherence source. The sample for which the optical distance needs to be measured between its interfaces is used as the end reflectors of the signal interferometer arm per

5   step 126. The reference mirror in the reference interferometer arm is scanned per step 128. The method includes the step 130 in which the reflections from the signal and reference arms are combined and separated by wavelength. Further, per step 132 the heterodyne oscillations in the intensities of the combined light are detected. The phases of the heterodyne signals for both wavelengths are then found via, for example, a

10   Hilbert transform or any alternate phase extraction method per step 134. A difference phase given by subtracting twice the phase of the longer wavelength from the shorter is evaluated for the whole scan per step 136. The scan is repeated with the wavelength of the light being slightly detuned per step 137. Steps 130-136 are then repeated.

The two difference phases found from the two scans are then superposed on each

15   other on a graph with the x-axis representing the displacement of the reference mirror per step 138. It should be noted that the extraction of difference phases can also be done with the appropriate light sources or chromatic filters or software/hardware signal processing on a single scan.

The next step in method 124 includes determining the phase crossing points on a

20   graph to mark the locations of the sample interfaces per step 140. By counting the number of times the heterodyne signal associated with the CW light wraps over by 2π between the two crossing points, the optical separation between the interfaces is

determined per step 142 with accuracy to about a fraction of a wavelength, for example, of approximately 0.2. By measuring the difference phase at the crossing points, further localization and/or refining of the separation to a very small fraction of a wavelength, for example, approximately 0.001.

5   In another preferred embodiment as illustrated in Figure 7 which is a schematic diagram of the system to measure optical distance, the low coherence light source may be sufficiently broad in bandwidth, for example, more than 4 nm. On the detection end, a third detector 174 is added to the two detectors 166, 176. This results in the low coherence light signal 168 being further split into two. Prior to reaching the detectors,

10   the two light beams are passed through different filters 170, 172. The filters transmit different parts of the spectrum. One passes the longer wavelength spectra component, while the second, the shorter wavelength spectral component. Preferably the two transmitted beams are separated in their spectrum by more than 2 nm.

The light beams are then incident on the detectors and their heterodyne signals

15   are processed in the fashion discussed with respect to Figure 1. The advantage of this method in accordance with alternate preferred embodiment is that the method eliminates the repetition of the process with an adjusted low coherence wavelength. The two signals are acquired in the same scan.

Figures 8A and 8B illustrate a flowchart 184 of an alternate method to measure

20   an optical distance in accordance with a preferred embodiment of the present invention. The method 184 includes the use of two harmonically related light sources in an interferometer one of which is a CW source while the other is a low coherence source.

The sample for which the optical distance needs to be measured is used as the end

reflectors of the signal interferometer arm per step 186. The reference mirror in the

reference interferometer arm is scanned per step 188. The method further includes the

step 190 of combining the reflections from the signal and reference arms and separating

5   them by wavelength. The low coherence wavelength is further separated using filters

per step 192. The method 184 includes the step 194 of detecting the heterodyne

oscillations with at least three detectors. The next step 196 includes detecting the

heterodyne oscillations in the intensities of the combined light. The phases of the

heterodyne signals for both wavelengths are then found via, for example, a Hilbert

10   transform or any alternate phase extraction method per step 198. A difference phase for

each low coherence signal with the CW signal is then evaluated per step 200.

The two difference phases are then superposed on each other on a graph with the

x-axis representing the displacement of the reference mirror per step 202. The

remaining steps 204, 206, 208 are similar to steps 140, 142, 144 as discussed with

15   respect to Figure 6B.

The preferred embodiment of the method can be used to absolutely measure

arbitrarily long optical distances with sub-nanometer precision. The preferred

embodiment of the system can be free space based or fiber based. Figure 9 illustrates a

preferred embodiment of a fiber based system to measure an optical distance.

20   The input light 256 includes approximately harmonically related low coherence

light having a wavelength λ_1 and a CW light beam having a wavelength λ_2 which travel

in fiber 251. The composite beam is divided in two, one part of the signal is incident on

the target lens 254 and sample 256 and travels in fiber 253 while the other is incident on

the reference mirror 266 via a lens 268 and travels in fiber 251. The movement of the

reference mirror introduces a Doppler shift on the reflected beam. The reflected beams

are recombined and then separated into their component wavelength components by

5   means of the dichroic mirror 258. These wavelength components are measured

separately with photodetectors 260, 262. The resulting heterodyne signals at their

respective Doppler-shifted frequencies are bandpassed around their respective center

heterodyne frequencies and Hilbert transformed to extract the corresponding phases of

the heterodyne signals, ψ_{CW} and ψ_{LC}.

10   The preferred embodiment methods can be used to make precise optical distance

measurements. From such measurements, optical properties of target objects can be

accurately measured. By measuring the dispersion profile of the target, structural and/or

chemical properties of the target can be evaluated. In the biomedical context, preferred

embodiments of the present invention can be used to accurately determine the

15   dispersion property of biological tissues in a non-contact and non-invasive manner.

Such dispersion determination can be used on the cornea or aqueous humor of the eye.

The sensitivity achieved can be sufficient to detect glucose concentration dependent

optical changes. In a preferred embodiment of the present invention method, the blood

glucose level can be determined through non-invasive measurements of the dispersion

20   profile of either the aqueous, vitreous humor or the cornea of the eye.

As discussed hereinbefore, phase based interferometry methods are able to

measure optical distances very sensitively. However, they are typically limited in their

applications by a problem that is widely known in the field as the 2π ambiguity

problem. The crux of this problem is that it is impossible to differentiate a length of

10.1 wavelengths from the length of 11.1 wavelengths. The preferred embodiments of

the present invention overcome this limitation and allow absolute optical distance

5   measurements with sub-nanometer accuracy.

There are numerous phase based methods that measure changes in optical

distances with a sensitivity of approximately the nm range. As long as the change is

small and gradual, the change can be continuously tracked. There are low coherence

methods that measure absolute optical distance by tracking the delay in arrival at the

10   detector of light reflected from different interfaces of the reflector sensitivity in

approximately microns. As discussed hereinbefore, the simultaneous use of a CW and a

low coherence light sources in an interferometer provides for the methods to measure

optical distance. The heterodyne phases of the signals associated with the two

wavelengths are intrinsically related. By processing the phase per the preferred

15   embodiments, motional noise is minimized and preferably eliminated from our

measurements.

An application of a preferred embodiment is the glucose level determination

using the measurement of the refractive index of the vitreous and/or aqueous humor of

the eye. The sensitivity of this technique affords the ability to measure chemical

20   concentrations with a sensitivity that is clinically relevant. One of the more obvious

applications of the method of a preferred embodiment is the determination of blood

glucose level through measurements performed on the eye. The glucose level of the fluid in the eye mirrors that of the blood with clinical insignificant time delay.

The method of a preferred embodiment measures the optical path lengths of the vitreous and/or aqueous humor layer in the eye at least two separate sets of wavelengths

5   as illustrated in Figure 10. The method measures the product of the refractive index at the low coherence wavelength and the physical separation between two interfaces. By changing the wavelength of the low coherence light source (and appropriately changing the CW wavelength to match), the refractive index difference at different wavelengths is measured. For example, one set of experiment is performed with a tunable 500 nm low

10   coherence light source and a one micron CW light source to extract $n_{500nm}L$ where L is the physical thickness of the vitreous and/or aqueous humor at the point of measurement. Another set of experiments is performed with a tunable 1000 nm low coherence light source and a 1800 nm CW light source to extract $n_{900nm}L$. By taking the ratio of these two measurements, the refractive index ratio, n_{500nm}/n_{900nm}, of the vitreous

15   and/or aqueous humor is extracted. With the existing sensitivity, for example, 0.5 nm optical path sensitivity, a preferred embodiment of the system, the ratio n_{500nm}/n_{900nm} with 10^{-8} sensitivity can be measured for a material of thickness equal to that of the human vitreous and/or aqueous humor. This provides the sensitivity to changes in the glucose level of about 0.25 mg/dl. Given that the typical blood glucose level is about

20   100 mg/dl, a preferred embodiment of the present invention is well suited for blood glucose assessment. The choice of optical wavelengths is flexible, the wavelength used hereinabove is simply for illustration purpose. For maximal sensitivity, the wavelength

separation is preferably as large as possible. Preferred embodiments include a

separation of greater than 500 nm.

In the event that such a refractive index ratio is insufficient for absolute blood

glucose level determination due to the presence of other chemicals that is changing in

5   the vitreous and/or aqueous humor, a more complete range of optical path length

measurement can be made at a range of other wavelengths. This set of more complete

measurement allows the determination of glucose level and other chemical

concentrations by fitting the measurements to known dispersion profiles of glucose and

other chemicals.

10   A preferred embodiment of the present invention can be applied as a

measurement technique in semiconductor fabrication. As the preferred embodiment of

the method is non-contact and non-destructive, it can be used to monitor the thickness

of semiconductor structures as they are being fabricated. In addition, the composition of

the semiconductor structures can be assessed in much the same manner as that discussed

15   with respect to the characterization of the vitreous and/or aqueous humor measurements.

The claims should not be read as limited to the described order or elements

unless stated to that effect. Therefore, all embodiments that come within the scope and

spirit of the following claims and equivalents thereto are claimed as the invention.